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A Physical Hypothesis for the Combustion Instability in Cryogenic Liquid Rocket Engines (Preprint)

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In this work, the author would like to portray a sketch of a *unified physical picture* to describe the coupling nature/strength between the chamber acoustics and the injectors. This new perspective is achieved through a physically intuitive argument combined with previously published test results for two popular injector designs, namely, coaxial and impinging jets. For the impinging-jets injectors, it is shown that the dynamic behavior of the dark-core (or breakup) zone for each jet, their lengths and thicknesses, has a profound impact on injector "*sensitivity*" to disturbances in its surrounding. This information is used to offer a possible explanation for the trends seen on the Hewitt stability plot in impinging-jet injectors.

INTRODUCTION

Acoustic combustion instability has been one of the most complex phenomena in liquid rocket engines, and therefore difficult to fully understand, control, and predict particularly in the design of large-output rockets. The difficulty arises from the emergence of oscillatory combustion with rapidly increasing and large pressure amplitudes. This leads to local burnout of the combustion chamber walls and injector plates which is caused through extreme heat-transfer rates by high-frequency pressure and gas velocity fluctuations, see Harrje and Reardon [1] and Yang and Anderson [2]. It is thought that resonance acoustic modes of the thrust chamber, amongst them the transverse modes being the most troublesome, are excited through the energy provided by the combustion. The amplification process is thought to include a feedback of information from the acoustic field to the injector or near-injector phenomena which in turn tends to reinforce the combustion-to-acoustic-field energy transfer processes. The underlying physics of this latter energy transfer is the widely cited general principle by Lord Rayleigh [3]. In essence, he stated that the interaction between the combustion heat release and the acoustic field is the strongest if heat is added in a region of space and at the time when the acoustic amplitude is the highest. Although this view has been useful, evidences gathered by past investigations attributed combustion instability to a complex interaction of the external acoustic field with the fuel injection (or near-injector) processes as a feedback mechanism, thereby leading to incidences of instability in rocket engines. For this and other reasons, controlled studies have been conducted probing into the effects of acoustic waves on gaseous and liquid jets from a variety of injector hole designs. A series of investigations concentrated on disturbances induced from within the injection system. They considered the effects of acoustic fields on many phenomena such as flow structure, vortex pairing, and shear layer growth rate in the initial region of the jet (for example, see a short review article by Kiwata, et al. [4]). More relevant to the work reported here, are a few reports and articles on gaseous and (in particular) liquid jets under the influence of external (transverse and longitudinal) acoustic fields. These have been reviewed in Chehroudi and Talley [5] and Davis and Chehroudi [6].

In this paper, however, the author would like to propose a *unified physical picture* based on experimental results and intuitive arguments to describe a possible coupling nature/strength between the chamber acoustics and injectors or near-injector processes in cryogenic liquid rocket engines.

DISCUSSION

In Davis and Chehroudi's [6] experimental work, we have offered a plausible explanation of why temperature ramping (progressive reduction of the propellant temperature for engine combustion stability rating purposes) and decreases in outer-to-inner jet velocity ratio (for shear coaxial injector) push a LOX/H_2 cryogenic liquid rocket engine (LRE) into an unstable zone. In Davis and Chehroudi's [6] non-reacting coaxial jet work at high pressures, where an externally-imposed acoustic field is used to simulate certain key aspects of their interaction in real engines, it is shown that at subcritical conditions the dark-core length root mean square (RMS) fluctuation values were much higher than those at near-critical and supercritical conditions by a factor of 4 to 6 at all velocity ratios. Also, as the outer-to-inner jet velocity ratio declines, the RMS value increases from 1-2 to values of about 7-8 inner jet hole diameters at subcritical pressures. Taking the RMS of the dense core as a reflection of mass fluctuations to a first-order approximation, combined with the measurements of a core dominant oscillation frequency consistent with the imposed acoustic field's resonant mode frequency, it was then suggested that a connection to rocket combustion instability could be obtained from these data through examination of the RMS of the dark-core length fluctuations. We stated the possibility that decreases in the dark-core length fluctuation levels (quantified through the RMS), interpreted as *reduced intrinsic sensitivity,* which were shown to occur at higher velocity ratios, could weaken a key feedback mechanism for the self-excitation process that is believed to drive the combustion instability in cryogenic LRE. This was offered as a possible explanation for the combustion stability improvements experienced in production engines under higher outer-to-inner jet velocity ratios. The effect of temperature ramping was linked to its impact on the outer-to-inner velocity ratio and hence was also explained. More details can be found in Davis and Chehroudi [6] and Ivett et al. [7]. In other words, *the dynamic behavior of the dark-core, specifically its length, is considered to be the primary culprit.*

It is noted here that measured mean (intact) dark-core length for SSME-like momentum flux ratios by Woodward et al. [8] in a LOX/GH_2 *fired* single-element rocket engine agrees with those of Davis and Chehroudi's [6] nonreacting case. And, in addition, existence of the dark-core length fluctuations has also been reported by Woodward et al. [8]. In a recent work published by Yang et al. [9], they performed tests in a *fired* single-element rocket equipped with a coaxial LOX/CH_4 injector. Measurements of the dark core length indicated an increasing trend in the level of fluctuations when the outer-to-inner velocity ratio was decreased and the core oscillation spectra showed more high-frequency contents in jet oscillation at lower velocity ratios. These results are consistent with the Davis and Chehroudi's [6] conclusions cited above.

Interestingly, results published in a LOX/GH2 (i.e., liquid oxygen/gaseous hydrogen) single-element coaxial-jet *fired* engine work by Smith et al. [10] (DLR group) also are consistent with the Davis and Chehroudi's view described above that high RMS values for the dark-core length, specifically at subcritical and low velocity ratios, may lead to or cause combustion instability. In their work, Smith et al. swept the engine from the ignition period into three consecutive steady-state phases of supercritical (phase 1), near-critical (phase 2), and subcritical (phase 3) chamber pressures, each sufficiently long for adequate measurements and allowing 2-4 seconds of transition in between phases. The intention was to investigate effects of the chamber reduced pressure (Chamber/Critical pressures) on the engine combustion instability. Under all conditions tested, the peak-to-peak pressure remained less than 3% and 2% of the mean chamber pressure for phases 1 and 2, respectively. For phase 3, however, conditions led to unstable combustion. In fact, under all test conditions they investigated, no instability could be triggered when operating above or very near to the critical point of oxygen. In another test, referred to as "V-test", chamber pressure was adjusted through propellant flow rate regulation while maintaining a constant fuel-to-oxidizer (F/O) ratio. During this test, under no conditions combustion instability was seen as long as chamber pressure was above the critical point of the oxygen, yet an unstable mode was triggered as soon as reduced pressure reached less than unity, see Fig. 1. More importantly, they showed significantly different appearances of the liquid oxygen core in different phases. Above and near the critical point of oxygen (phases 1 & 2) the oxygen core flow appeared very steady (implying low RMSs) with surface perturbations reducing as chamber pressure approached critical point. They also reported that below the critical point of oxygen (subcritical pressures), the LOX jet experienced "*increased oscillation and general unsteadiness*" (implying high RMSs). The initially undisturbed flow became unsteady at approximately 15-20 LOX jet diameters downstream from the injector exit plane. Therefore, very low RMS values of the dark-core length at near- and super-critical conditions and high RMS values at subcritical pressures, both measured by Davis and Chehroudi [6] in their *nonreacting* experimental setup, are consistent with the *fired*-engine experimental observations by Smith et al. Hence, their reported unstable combustion behavior at subcritical pressures with high core unsteadiness correlates with Davis and Chehroudi's high RMS values at subcritical conditions, interpreted as conditions leading to highly "sensitive" dark-core dynamic response to its surrounding.

One is then tempted to expand the same idea explained above for coaxial jets to impinging-jets injectors (say, like-on-like, or LOL, type). In other words, the following questions are posed. Conceptualizing that each individual circular jet of an impinging injector possesses a dark-core (or break-up zone) with its averaged length changing according to the Chehroudi et al. [11] (or similar) equation [~(d_j)*sqrt(liquid density/environment density); see Fig. 2] and each having a certain RMS level of fluctuations, what would be the implication of a situation when the averaged core length approaches the same order of magnitude as the distance from the exit hole to the impinging point? Under what conditions such a scenario could happen? Is it possible to have such a situation in a practical rocket engine? Figures 3 and 4 schematically show the two scenarios that would intuitively exhibit completely different dynamic behaviors as a system. Let us consider a startup event when the chamber pressure begins from an atmospheric value (~100kPa) to where a steady high pressure and temperature condition is established. The mean core length will then change according to a Chehroudi-like (or equivalent) equation and, under supercritical chamber pressures, could even reach a negligibly small value (see Davis and Chehroudi [6]). Hence, one would expect that the nature of the impingement continuously changes in time as chamber pressure increases. Therefore, at a certain chamber pressure (call it a threshold, P_{th}), the averaged (un-impinged) core length, $L_{C,Pth}$, becomes short enough, say, of the same order as the distance from the exit holes to the impingement point, to be of importance in dominating the dynamic behavior of the injector unit, see Fig. 4. Considering the high RMS levels of the core length fluctuations for each jet of an impinging injector, one can then intuitively regard this system (at the dark core length equal to $L_{C,Pth}$) as highly unpredictable and, more to the point, being very *sensitive to (and responsive to) ambient disturbances.* This is especially so for impingement targeting when a wiggly shape is superimposed under an externally-imposed acoustic field. In a sense, the feedback link or coupling between the environment (acoustic field) and the injector becomes very strong, somewhat similar to the effect of the velocity ratio seen on the sensitivity of the coaxial injector dark-core length to its environmental acoustic disturbances. This way, one has a sketch of a ***unified physical picture*** for the (feedback) linkage between the chamber acoustics and the injector through the dynamics of the dark core (or the break-up zone) of the liquid propellants. Although the dark-core length reaches (and passes, that is, becomes shorter than) the $L_{C,Pth}$ value at high chamber pressures approaching supercritical conditions, it could also become sufficiently close to it if the engine operating pressure range includes the P_{th} value. There are host of other ways that the $L_{C,Pth}$ can be reached and are discussed later.

Note that under the situation described in Fig. 4, there are two factors contributing to impinging-jet injector hypersensitivitity. First, the fact that the average length of the dark-core is now too short for a robust impingement, and the second is that the mean jet cross-section at the impingement point is sufficiently reduced from its nominal value of injector hole diameter for good targetting. For example, Chehroudi et al. [5] showed pinching of a single round LN2 jet (into GN_2 ambient) at as close a distance as five (5) jet diameters when an acoustic field is externally imposed. The effect was relatively more dramatic at subcritical chamber pressures and substabntially subdued at supercritical values. At the same time, the breakup length was affected as well. Both effects (though could happen independently) would reinforce the hypersensitivity of an impinging-jet injector unit. Note that changes in the dark core (or breakup zone) length and thickness occur both through changes in mean values of thermofluid parameters (chamber pressure (P_{ch}), chamber temperature (T_{ch}), velocity, etc.), for example, when engine thrust level is varied, as well as through level of their fluctuations (depending on the ferquency, of courese).

On the other hand, let us now look at the Hewitt correlation (see Anderson et al. [12]). This correlation suggests that for LOL impinging injectors (and certain similar class), as one decreases the dn/V value from an stable operating condition, engine will be eventually pushed into an unstable operating mode at a certain critical dn/V value [$(dn/V)_c$]. Here, dn is the injector hole diameter and V is the injection velocity for the impinging jet injector. There have been a few proposed mechanisms, such as jet atomization frequency (Anderson et al. [12]), flame straining/extinction (Kim and Williams [13]), and fuel jet aerodynamic excitation (Chao and Heister [14]) attempting to offer explanations of the trend seen in Hewitt correlation. Although none has been fully proven as an established fact and a combined effect of several mechanisms can be in play, the author's hypothesis is a new perspective to the list. An attempt to decrease the dn/V ratio implies either reduction of the dn or an increase of the V or both. Generally speaking, an increase in V tends to shorten the dark-core (or break-up) length (stronger interaction through enhanced aerodynamic interaction) in the 1st, 2nd wind-induced liquid jet breakup regimes, using the terminology proposed by Reitz and Bracco [15]. This is shown in Figs. 5 and 6 along with the corresponding terms used by Hiroyasu [16]. With injection velocities in the order of 20m/s or higher (typical rocket operation), a jet is in the 1st, 2nd wind-induced breakup regimes at lower pressures and in the (full) atomization regime at sufficiently high pressures. In the former cases (i.e., the wind-induced), the length is affected both by injection (relative) velocity and density ratio, whereas in the latter, the density ratio is more dominant (see Figs. 2, 5, and 6). Hence, reduction in the dark core (or breakup) length is expected when V is increased in Hewitt stability parameter as shown in Figs. 5 and 6. Also, in an operating engine, increases in V (higher thrust) will be followed by higher chamber pressures which impact the dark core length even more dramatically. At the same time, a reduction in the dn (or dj) also reduces the dark-core length according to Chehroudi's equation, see Fig. 6. Note that the dj in Chehroudi equation is the exit jet diameter and intended to capture inner-nozzle effects (such as hydraulic flip and cavitation) to a certain degree, whereas the dn in the Hewitt is a fixed hole diameter for a given design because the actual jet exit diameter is not usually known (measured or measurable) in real engine chamber environments. Nevertheless, reduction of the dn/V through changes in either dn or V leads to shortening of the mean dark-core (or break-up) length for each jet in an impinging jet injector. Then, it is quite possible that as dn/V is reduced in an engine, the mean dark core length reaches a critical value ($L_{C,Pth}$) where one intuitively expects *inherently high sensitivity* for an impinging-jet system to environmental acoustic field. *Here, the author is hypothesizing that the Hewitt stable-to-unstable transition point (or line) as dn/V reduces is at or near where the distance from the holes exit plane of the impinging injector to the impinging point (i.e., pre-impingement length) reaches a critical value ($L_{C,Pth}$), creating a situation somewhat similar to what is shown in Fig. 4.*

Although larger values were also used, according to Ryan et al. [17], the pre-impingement length (along the jet) is typically 3.5 to 11.5 hole diameters. For example, for the Lunar Module Ascent (LMA) injector, it is about 6 to 8 hole diameters (CPIA 245 & 246 [18]). Measurements published by both Chehroudi et al. [19, 20] and those by the DLR group indicate that the *mean* dark core length of a single liquid nitrogen jet at moderate to high chamber pressures progressively shortens, for example, from 12 to a value of about 7 hole diameters, see Fig. 7. The two injectors had hole lengths of 40 and 100 times larger than their diameters. Hence, under normal operation, it is expected to provide a longer dark-core (breakup) length as compared to those used in rocket engines. In addition, considering that the data in Fig. 7 is for injection into the room temperature, entrainment of hot gases in thrust chambers is expected to shorten this core length even more due to enhanced evaporation. This may, in part, be a reason for the general finding that displacement of the combustion zone closer to the injector face increases susceptibility for combustion instability, see Oefelein and Yang [21]. Considering high RMS values of the dark core (or break-up) length, this suggests feasibility of conditions that the pre-impingement and dark core lengths are sufficiently close to cause hypersensitivity and high responsiveness to environmental oscillations and disturbances. For example, with a RMS (or standards deviation) value of 4 hole diameters, assuming normal distribution, the instantaneous dark-core length is between +/- 8 hole diameters of its mean value 95% of the time. With mean core length of 12 hole diameters, it will penetrate into or have overlap with the pre-impingement-length region. Importance of the pre-impingement length and its impact on the characteristics of the impinging-jet injector has also been reported by Ryan et al. [17]. One reads in this work, "Variations of pre-impingement length had a measurable effect on (sheet) breakup length and drop size, pointing to the importance of the jet condition prior to impingement."

Although performed under steady conditions, the higher "*sensitivity*" of the impinging jet injector can also be discerned/inferred in Figs. 8 and 9 taken from Anderson et al. [12] work where large differences between the *sheet breakup lengths* for different pressures and impinging-jets included angles (2θ) are clearly seen at low values of the dn/V stability parameter. For example, Fig. 9 strongly suggests higher sensitivity of the injector when V is reduced, simply by the enlarged size of the scatter bounds at any given pressure, and sensitivity to pressure changes at low V values. Although strictly speaking one should have its frequency response (amplitude & phase) measured, the author takes these results as indicating a high probability and a strong suggestion for injector hypersensitivity. On the other hand, accepting the proposed hypothesis (see Fig. 4), then one expects a higher level of unsteadiness (and sensitivity) on the *sheet break-up length.* Examination of the results in Figs. 8 and 9 is reinforcing. This sheet-breakup-length *enhanced sensitivity* seen in Figs. 8 and 9 is in agreement with the similar trend derived by the hypothesis which implies elevated sensitivity when the mean length of each (or one of the) circular jet's dark-core zone reaches a critical value ($L_{C,Pth}$) or the same order as the distance from the hole exit plane to the impinging point. In addition, at a given pressure (or included angle) the *data scatter band* shown in Figs. 8 and 9 is also largest at low dn/V values, again and consistently suggesting a more erratic/chaotic dynamic behavior, being in congruence with the "*sensitivity*" trend predictions of the proposed hypothesis. An individual, unaware of the hypothesis proposed here, seeking the causes of this hypersensitivity in Figs. 8 and 9, would also consider searching features arising from each jet (and also hole geometrical designs) of the impinging jet injector as one top and potential candidate.

Considering what was discussed for the coaxial jet injector, one implication of the hypothesis is that an impinging jet injector engine should be more stable at sufficiently high pressures, such as supercritical conditions. This is because not only the RMS of the core length fluctuations declines substantially, but also the length of the core may become adequately shorter than the pre-impingement length depending on the geometrical dimensions of the impinger. The changes in the dark-core (break-up) length can also be inferred by examination of Fig. 10, showing a progressive increase in chamber pressure up to a supercritical condition for liquid nitrogen injection into gaseous nitrogen environment with no externally-imposed acoustic field. The long pre-impingement length seen along the jet is expected due to L/dn of about 100 which was intentionally designed to obtain a fully-developed condition at the hole exit plane. Obviously, shorter dark core is achieved for lower (injector hole) L/dn values used in LRE. Not only the dark core length of each individual jet is reduced as supercritical pressures are approached (as before and expected), but the jet also thickens. The impinger is expected to pass through a situation described in Fig. 4 as chamber pressure is increased. Hypersensitivity is anticipated at that condition according to the hypothesis. Progressive increase of chamber pressure beyond this point sufficiently thickens each jet and shortens the dark core length to a situation that the two dark-core lengths are shorter than the pre-impingement distance and a gas-like jet is impinging another gas-like jet with enlarged cross-section areas. Based on the hypothesis proposed here and given that RMS of the dark core is much lower at supercritical than subcritical conditions, a more robust (targeting and mixing) and less sensitive impinging jet system would be expected at supercritical chamber pressures. However, it is likely that the dynamic behavior of the potential core plays similar role as the dark core under this latter condition.

An example is given here to show the feasibility of unexpected dramatic and/or gradual changes in the dark core (or break up) length leading to a situation described in Fig. 4. The breakup length has been shown to be sensitive to events inside the injector as injection velocity or chamber conditions are changed. For instance, Tamaki et al. [22] recently showed that when cavitation occurs and, if bubbles collapse inside the injector (leading to higher hole exit-plane turbulence levels), it will enhance jet-breakup/atomization and causes a sudden decrease of the breakup length, see Fig. 11. On the other hand when a hydraulic flip is seen, it leads into a sudden increase (or decrease when it disappears) of the breakup length. This is just an example to show that when conditions change causing increases in V in the dn/V stability parameter, it is quite possible that either a gradual or sudden reduction of the dark core (or break up) length is experienced, leading to a situation described by the hypothesis causing hypersensitivity of the injector unit to chamber acoustic field oscillations. Obviously, the cavitation and hydraulic flip phenomena depend on the type of the propellant used, injector internal geometry, and operating conditions, compounded by drastic changes in its onset and behavior under *transient/unsteady or oscillating operation* which is rarely characterized. Hence, the cavitation state inside the hole under unsteady conditions is unknown and just recently being addresses by the research community. Therefore, not only pre-impingement length and the jet dark-core (breakup) length can approach each other at sufficiently high pressures and velocities, but there are other phenomena (such as cavitation, hydraulic flip, etc.) that can act in such a way to bring about injector hypersensitivity of the same nature as that described in Fig. 4.

The hypothesis proposed here has the advantage (simplicity and the beauty as well) of unifying the possible cause of the combustion stability irrespective of the design of the injector (at least for two popular cryogenic impinging and coaxial cases) as described above. What remains, amongst others, is to closely examine the historical data on the *dynamic characteristics* of the dark-core (or break-up) length (and width) for the circular jets forming the impinging injector for the propellant of interest and under the realistic thrust chamber conditions (which is quite rare or nonexistent) to further substantiate that a critical value, $L_{C,Pth}$, is reached when the onset of instability is detected in an engine. Also, *dynamic* characterization of each jet forming the impinging injector and when the two jets meet, in presence of an externally-imposed acoustic field, is highly desirable to assess sensitivity of the dark-core or breakup length of the jet to relevant design and operating variables.

SUMMARY and CONCLUSION

In summary, based on measured intrinsic sensitivity of the dark-core length in a coaxial-jet-like injector, a hypothesis is proposed to address a similar phenomenon in impinging-jet injectors, attempting to unify the underlying reasons for the injector-caused combustion instabilities in LRE. The basic premise here is that when an important dynamic feature (dark-core or breakup zone) of an injector design becomes sufficiently sensitive to thermofluid parameters of its environment, it is highly likely that this could strengthen the feedback link thought to be critical in the amplification process and hence push the system into an unstable operating state. Evidences are cited in support of the *enhanced sensitivity* of impinging-jet injectors to their environment when the mean dark-core (or break up) length of one or both jets forming the impingement reaches a critical value, being of the same order as the pre-impingement length. Feasibility of such a scenario is explored by comparing the range of pre-impingement length values and some recently measured dark-core lengths for cryogenic jets at density ratios of interest. The proposed hypothesis is able to offer a consistent explanation of why an engine design based on impinging jets goes unstable when Hewitt stability parameter (dn/V) is decreased. While work is needed to make a transition from a hypothesis to an established fact, there is sufficient published information in favor of the hypothesis to make it a strong possibility amongst others previously proposed. More investigation on the dynamic behavior of the dark-core length and width in impinging-jet injectors is justified and recommended.

Note: The terms "breakup" and "dark-core" lengths were interchangeably used here although strictly, the former is for the 1st and 2nd wind-induced, and the latter is used for the atomization regimes (dark core or intact core).

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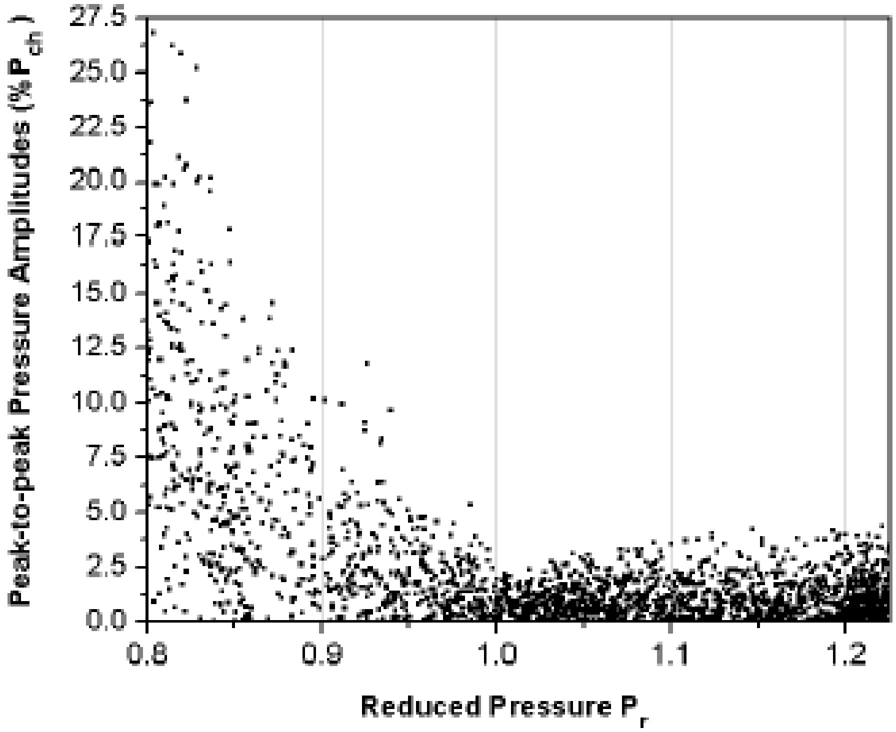
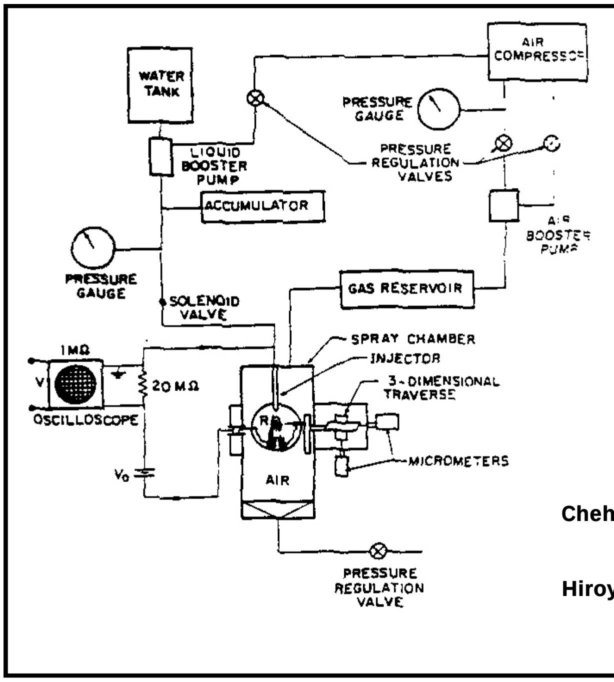


Figure 1. Peak-to-Peak chamber pressure oscillations for the V-test, showing a minimum value at a chamber pressure equal to the critical point of the oxygen. Smith et al. [10].



$$\frac{x_1}{d_j} = C\left(\frac{\rho_\ell}{\rho_g}\right)^{1/2}$$

Chehroudi et al. : 3.3< C <11
C=7.15 Recommended

Hiroyasu: C= 15.8

Figure 2. Intact core (dark core) length equation of Chehroudi et al. [11], showing density ratio dependency. The x_l and d_j are the intact core (or dark core) length and measured jet diameter at the exit of the injector, respectively. ρ_l and ρ_g are liquid and ambient gas densities.

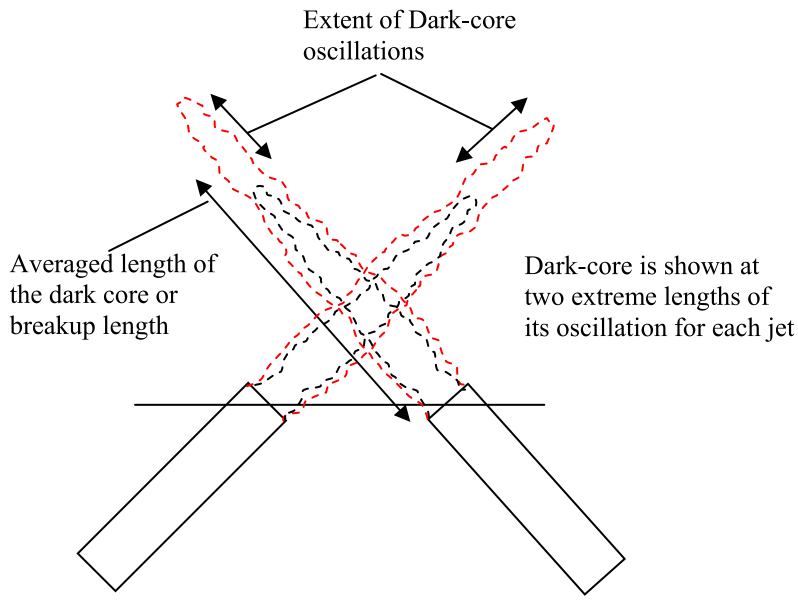


Figure 3. Shows the dark-core (or break-up) lengths of individual jets of an impinging injector for a situation when the average length is much larger than the distance from each hole to the impinging point. In actual operation, however, a liquid sheet is formed which breaks up at a distance from the impinging point. Under the scenario shown here, a robust and steady sheet is expected as a result of impingement, being relatively insensitive to its environmental distubances.

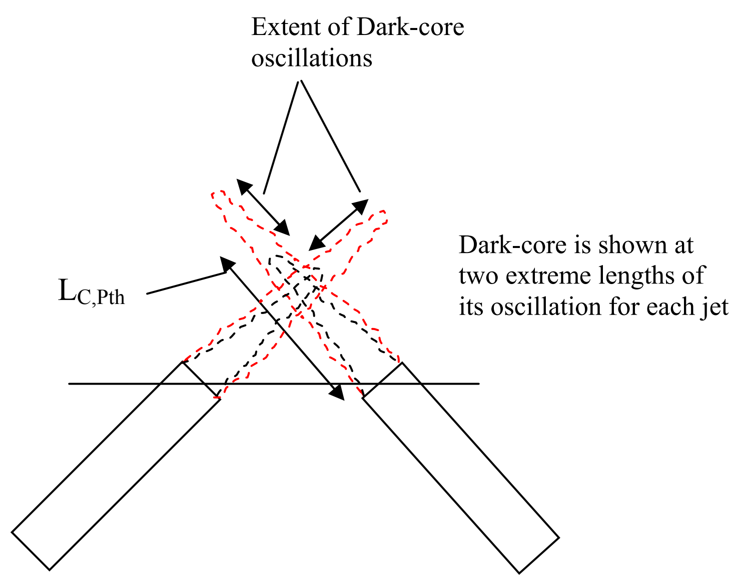


Figure 4. Shows the dark-core (or break-up) lengths of individual jets of an impinging injector for a situation when the average length is of the same order as the distance from each hole to the impinging point. In addition, the averaged jet cross-section at the impingement point is substantially reduced, being smaller than the hole diameter. In actual operation, however, under this scenario, a highly unsteady liquid sheet is expected as a result of the impingement, being highly sensitive to its environmental disturbances.

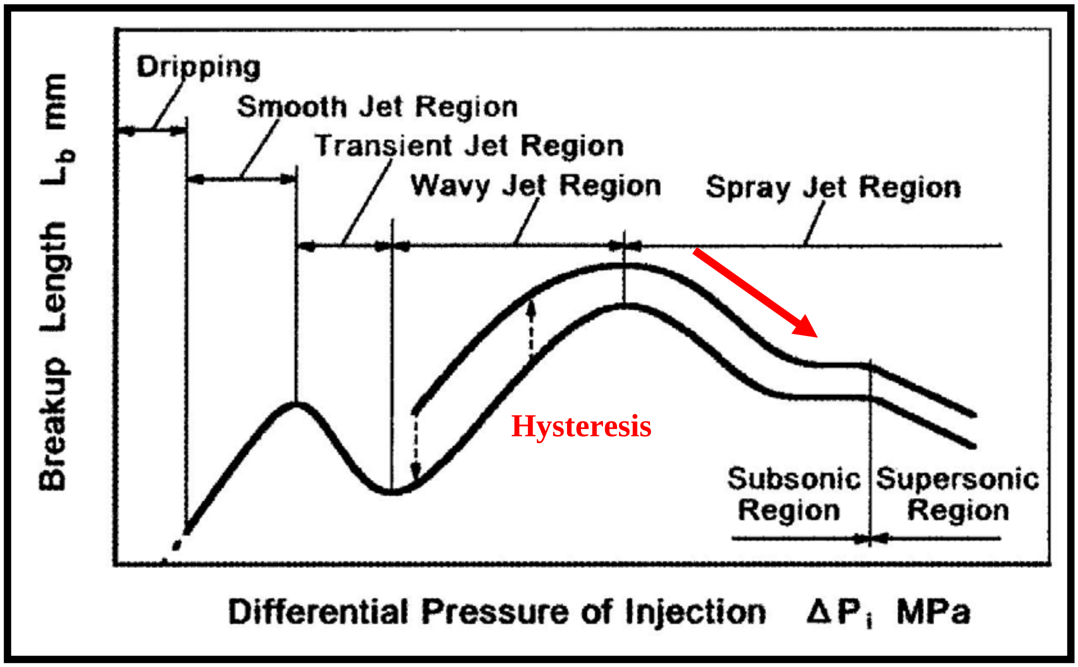


Figure 5. Mean breakup length of a circular jet as a function of injector differential pressure (which is proportional to jet velocity, V). A hysteresis phenomenon is observed. Note the decline of the breakup length with injection velocity in the region of interest. Hiroyasu [16].

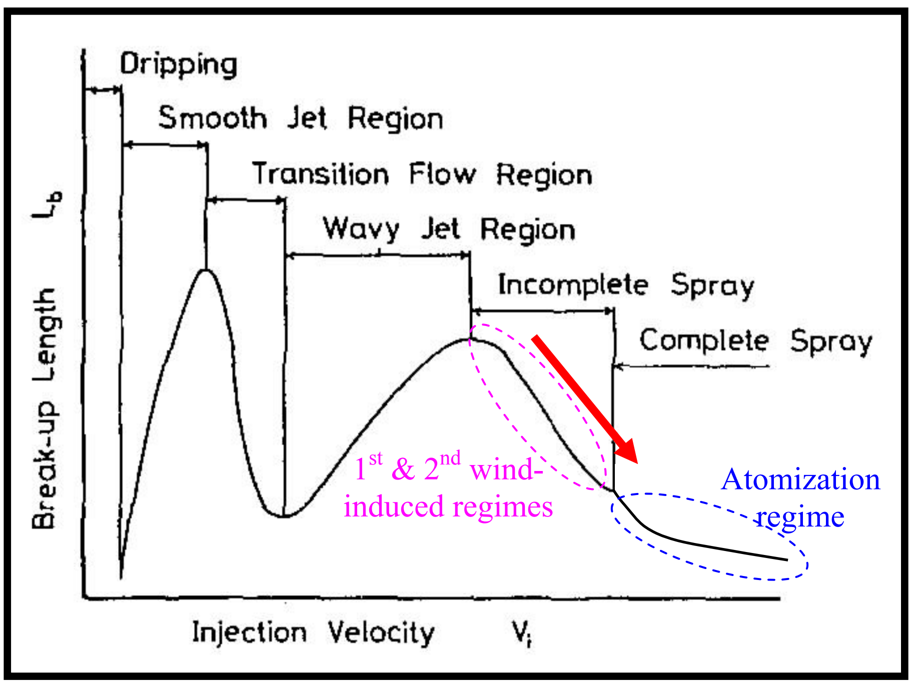
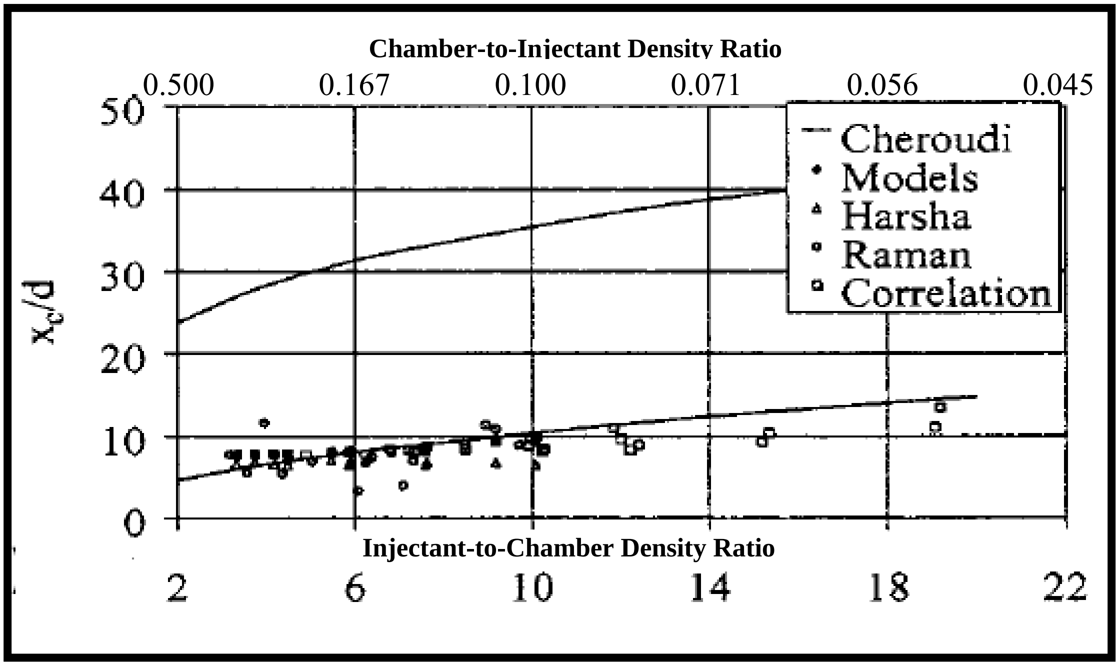


Figure 6. Mean breakup length of a circular jet as a function of the injection velocity, V. Note the decline of the breakup length with injection velocity in the region of interest. Hiroyasu [16].



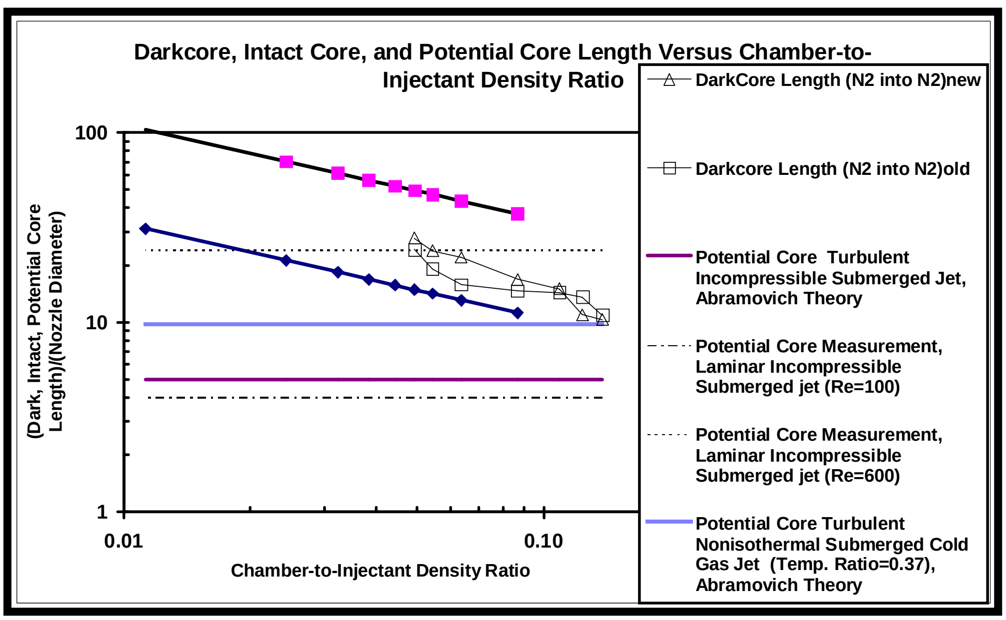


Figure 7. Comparison of the *mean* dark core length measurements for LN_2 jet injection into GN_2 at room temperature from sub- up to supercritical pressures. Also, shown are boundaries using Chehroudi's dark (intact) core equation (solid pink and blue diamond symbols). Note that the horizontal axis of the two plots are inverse of each other. Chehroudi et al. [19, 20].

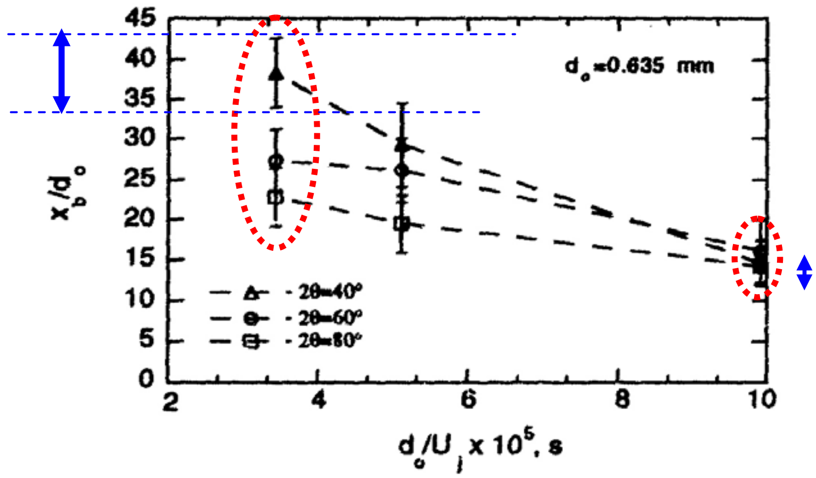


Figure 8. Shows *sheet breakup length* as a function of instability parameter at three different impingement included angles. Much higher sensitivity of the *sheet breakup length* is seen with included angle (2θ) at low dn/V (= d_o/U_j, in the original article) values. Also, the length of the error bars (or scatter bounds) is interpreted as a manifestation of the sensitivity level of the impinging jet to the included angle. Anderson et al. [12].

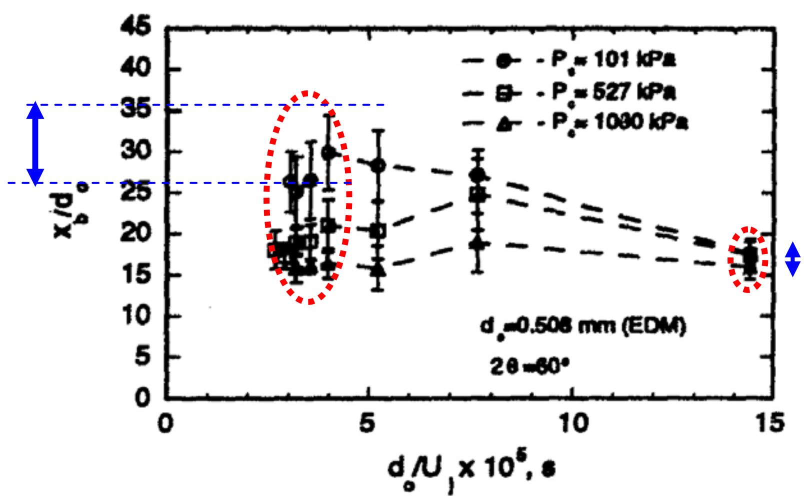


Figure 9. Shows *sheet breakup length* as a function of instability parameter at three different chamber pressures. Much higher sensitivity of the *sheet breakup length* is seen with chamber pressure at low dn/V (= d_o/U_j, in the original article) values. Also, the length of the error bars (or scatter bounds) is interpreted as a manifestation of the sensitivity level of the impinging jet to the ambient pressure. Anderson et al. [12].

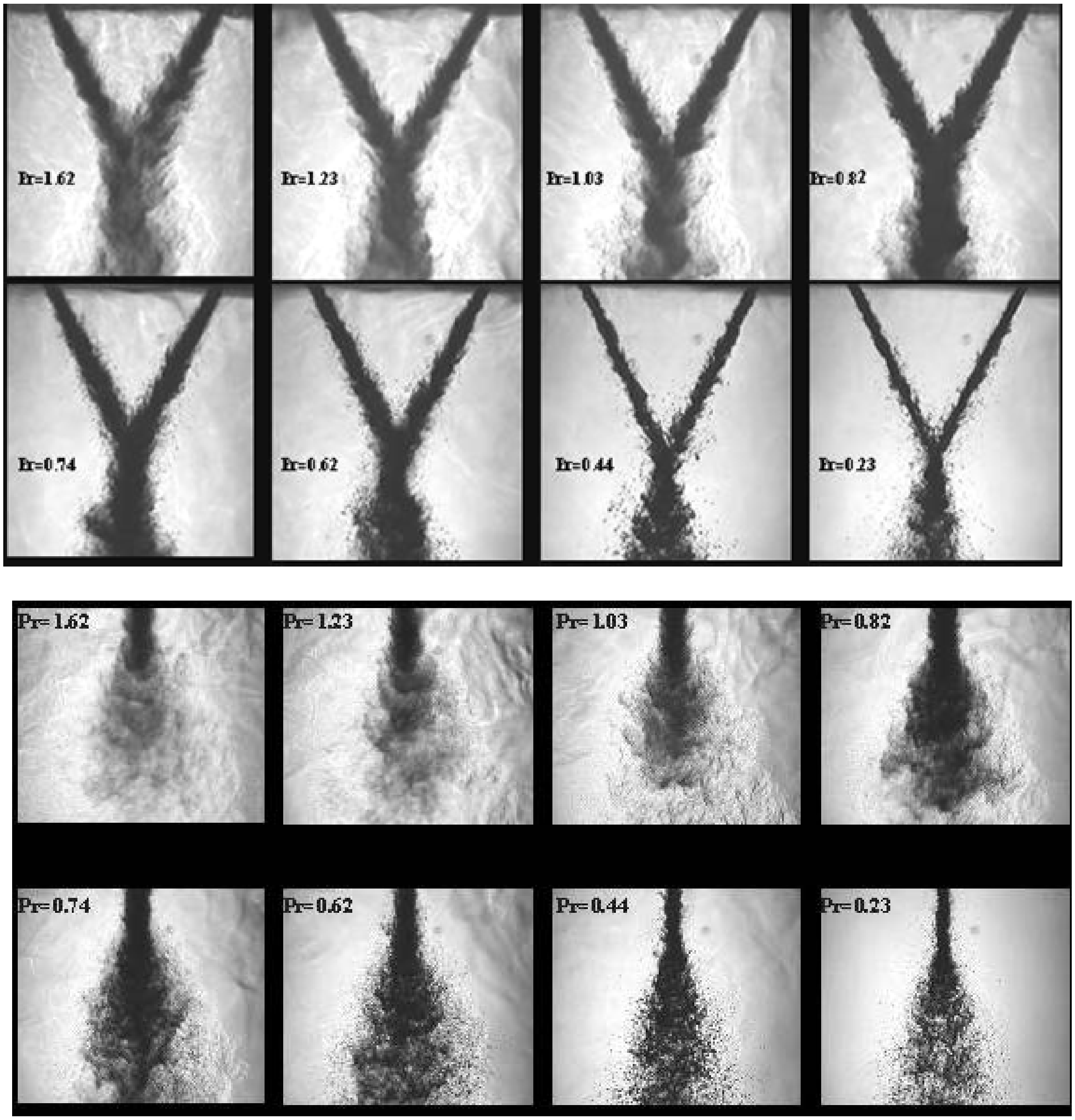
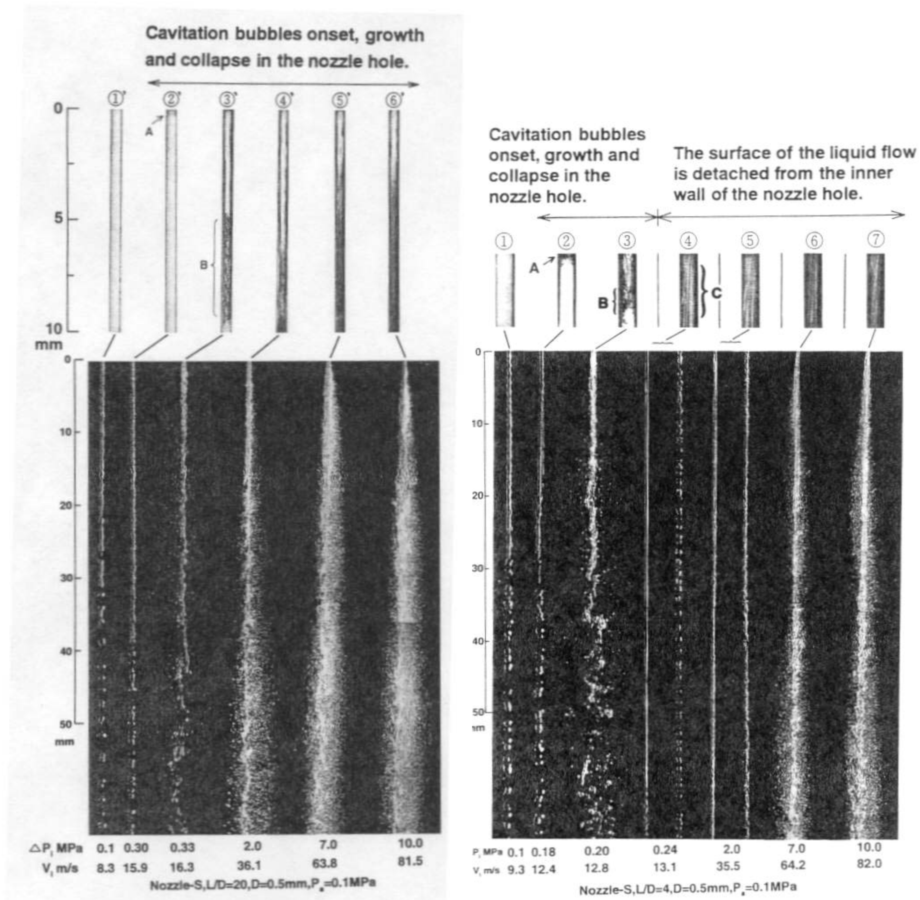


Figure 10. Instant images of sub-, near-, and super-critical impinging jets for LN2 into GN2 (room temperature) injection by Chehroudi. Last two rows show the same injector in the first two rows but viewed at 90 degree angle. P_{ch} = 0.8, 1.5, 2.1, 2.5, 2.8, 3.5, 4.2, 5.5 MPa; from lower right to upper left, (P_{ch} = 100, 200, 300, 350, 400, 500, 600, 800 psig; from lower right to upper left). (For nitrogen: $P_{critical}$ = 3.39 MPa; $T_{critical}$ = 126.2 K). Although the pre-impingement point is longer than typical practical injectors (~15 hole diameters) because of long hole L/dn, it is meant to accentuate the effects of chamber pressure on the nature of the impingement. (Re=25,000 to 70,000; hole L/dn~100; no cavitation; injection velocity:10-15 m/s)



(b) L/dn= 20

(a) L/dn= 4

Figure 11. Internal flow in the nozzle hole and disintegration behavior of the liquid jets (effects of L/dn). The breakup length measured by the Hiroyasu's group as a function of injection velocity is shown. It is indicated, for example, that when cavitation bubbles form but collapse inside the injector, enhanced atomization and consequently shorter breakup lengths are achieved. However, when a hydraulic flip occurs, it tends to increase the breakup length. ΔP_i and V_i are injector differential pressure and velocity. Tamaki et al. [22].